THE WELDING METALLURGY OF SOME COMMERCIAL TITANIUM BASE ALLOYS

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THE WELDING METALLURGY
OF SOME
COMMERCIAL TITANIUM BASE ALLOYS

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A B S T R A C T

During the past decade the importance of titanium alloys in engineering applications (particularly in the aircraft industry) has led to considerable research activity. The welding metallurgy of titanium alloys requires intensive investigation.

Titanium has been successfully welded by various methods. Employing the knowledge gained from a study of these methods, a welding machine was constructed and used successfully to weld commercial titanium.

The purpose of this investigation was to determine the weldability of the commercial alloys, Ti-5%Al-2.5%Sn and Ti-6%Al-4%V and to correlate the welding technique with the metal structure and mechanical properties.

Metallographic examination of welds made in the alpha alloy (Ti-5%Al-2.5%Sn) revealed a very coarse grain structure in both the weld and heat-affected zone. Bend tests indicated good ductility as-welded, and tensile tests showed a joint efficiency of 100%. This alloy had excellent weldability. The results on this alloy indicated the welding machine would be suitable for laboratory welding of titanium base alloy test plates.

Welds produced in the alpha-beta alloy (Ti-6%Al-4%V) had low ductility as-welded. A stress relief postweld heat treatment at 850°C recovered a large percentage of the lost ductility. The welds had a joint efficiency of 100% as shown by the tensile test results.

X-ray diffraction examination established the structure was almost entirely hexagonal. This same structure was present in the weld and parent metal.

A stress relief postweld heat treatment in an argon atmosphere produced beneficial results at 850°C, but deleterious results were obtained with stress relief at higher temperatures.

Stress relieving in air at a temperature of 850°C, followed by descaling, produced equivalent results to those obtained with heat treatment in the controlled atmosphere.

The alpha-beta alloy (Ti-6%Al-4%V) is weldable, as established in this investigation, but to regain equivalent properties to the original hot-worked and annealed condition requires postweld heat treatment.

ACKNOWLEDGEMENTS

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INTRODUCTION

Industry makes a never ending search for lighter and stronger metals to meet the requirements of modern machines, aircraft and missiles. Titanium and titanium alloys have attracted considerable attention in the past decade because of their high strength-to-weight ratio. Titanium is sixty percent heavier than aluminum but only fifty-six percent as heavy as steel. Because of titanium's resistance to many corrosive media, the chemical industry is conducting a great deal of research to determine suitable applications for titanium and titanium base alloys.

To utilize the light metals to best advantage they must be fabricated into structures with a minimum of joint material. In the chemical industry, where weight of a unit is not always a factor, economy of construction is essential. Fusion welding is the most efficient method of obtaining high-strength joints. The welding of titanium and its alloys has always presented a problem because of the affinity of titanium for active elements and compounds at elevated temperatures, specially for the ingredients of the atmosphere. Nearly

all the high-strength commercial alloys suffer embrittlement in the heat-affected zone and the weld metal in the as-welded condition.

Flux or flux-coated electrodes, as used in conventional methods of welding, contributed to the extreme embrittlement of the weld. Inert gas shielded metal-arc welding is the only arc-welding process that has proven satisfactory for joining titanium and its alloys. Earliest success was obtained by welding in a chamber containing an inert atmosphere.[1] Argon or helium, or mixtures of these two gases furnished adequate protective covering.[2] Later investigators established that titanium could be welded providing air could be excluded from the weld zone. The surface of the weld is protected by gas flowing through the welding torch. Protection of the underside of the weld is accomplished with the use of backing-strips of titanium fastened securely to the base metal. Another method of protection is provided by the use of a second operator directing a stream of argon to the underside of the weld. The most widely used method of protection, is to construct a small compartment under the weld to which inert gas may be directed.[3]

Titanium has been successfully welded by both manual and machine welding. Copper, brass or steel chill

bars placed on both sides of the weld have been used to reduce the time for which the weld requires inert gas protection. A clean surface is essential to minimize contamination and porosity.(3,4,5,6) Close control of other variables, such as arc-length, welding speed, joint design, edge preparation and fit-up are essential.

Previous work has shown that the alloys containing up to 6% aluminum, singly or in combination with tin are readily weldable and have good ductility and medium strength as welded.(7) Few of the high strength alloys are considered weldable, as most suffer severe embrittlement in the weld and heat-affected zone. One notable exception is the alloy Ti-6% Al-4% V investigated by Daniel M. Daley, Jr., and Carl E. Hartblower.(16) Their findings were that welds in this alloy have approximately 100% tensile joint efficiency at an ultimate tensile strength of 150,000 psi and 10 ft-lb of V-notch Charpy-impact energy at -40°C. The notch toughness is considerably greater in the heat-affected zone than is shown by other commercially available alpha-beta titanium alloys.

The purpose of this investigation is to utilize the known methods of welding titanium, to construct an apparatus to weld titanium and to adapt the equipment to weld titanium alloys. Also, to determine the physical properties of the alloy welds and to correlate these with weld microstructure.

CLASSIFICATION OF TITANIUM ALLOYS

The classification of titanium alloys developed over the past few years, and generally accepted by the industry, is based on the structure of pure titanium.

Titanium, at room temperature, is a close-packed hexagonal structure which, when heated, undergoes a transformation at 882°C to a body-centered cubic structure.(8) The close-packed hexagonal structure has been designated alpha and the body-centered cubic, beta. The titanium alloys fall into three broad classifications based on the characteristic effects the major alloying elements have on the alpha to beta transformation temperature of pure titanium.

1. Alpha Alloys contain elements which raise the transformation temperature, so stabilizing the alpha phase. Aluminum is the most widely used element in the manufacture of alpha alloys.
2. Beta Alloys contain elements which lower the transformation temperature, hence stabilizing the beta phase. Several elements are beta stabilizers. Chromium, manganese, iron, molybdenum and vanadium are used commercially.
3. Alpha-beta Alloys contain a combination of the alpha and beta stabilizing elements. At the present time, the largest percentage of com-

mercially produced alloys are of the alpha-beta type.

Some elements neither raise nor lower the transformation temperature and are considered neutral elements. Tin and zirconium fall in this class and are used in titanium alloys to supplement the more effective alpha or beta stabilizing elements.

MATERIALS USED IN THE INVESTIGATION

Commercially pure titanium, an alpha alloy (5%Al-2.5%Sn balance titanium) and an alpha-beta alloy (6%Al-4%V balance titanium), were selected for evaluation of their weldability.

Investigation has shown that the majority of the beta alloys are considered unweldable and the Battelle Memorial Institute has shown that the maximum total content of the beta stabilizing elements is 3 - 4% for acceptable ductility in titanium alloy weld deposits.[9, 10]

When this study was undertaken there were few commercial alpha alloys being produced, the alloy containing 6%Al-4%V in the as-rolled annealed condition suggested an interesting and useful study of its weldability.

Strip was selected because of its availability and its wide application as a structural material in the aircraft and commercial industries.

The materials were supplied by the Titanium Metals Corporation of America. Their specifications are shown in Table I.

"Commercially pure" titanium and its alloys are available in several degrees of purity. Oxygen, nitrogen and hydrogen are impurities in all titanium products but are limited to acceptable maxima as shown in Table I.

The material was received in the hot-worked and annealed condition, with a small grain size and contaminants well dispersed throughout the structure.

TABLE I SPECIFICATIONS FOR TMCA*MILL PRODUCTS

TMCA Grade Designation	Heat No.	Size Lgth.	Size Wdth.	Size Thk.	Chemical Analysis Weight %
Ti-55A	M6334	Rand.	3"	.032"	C = 0.08 max N_2 = 0.05 " Si = 0.05 " H_2 = 0.015" Fe = 0.12 " O_2 = 0.15 "
Ti-5Al-2.5Sn	M6218	Rand.	3"	.050"	C = 0.15 max N = 0.07 " H_2 = 0.20 " Fe = 0.5 " O_2 = 0.20 " Al = 4.0 - 6.0 Sn = 2.0 - 3.0
Ti-6Al-4V	M5257	Rand.	3"	.050"	C = 0.08 max N_2 = 0.05 " H_2 = 0.015" O_2 = 0.05 " Fe = 0.25 " Al = 5.5 - 6.5 V = 3.5 - 4.5

TMCA Grade Designation	Guaranteed Mechanical Properties Sheet and Strip (as mill annealed)	
Ti-55A	Yield Strength Tensile Strength Elongation, 2" Sheet Bend, 105°	= 45,000 - 65,000 Psi = 55,000 Psi min. = 22 Pct. min. = Under 0.070" - 2T Over 0.070" - 2.5T
Ti-5Al-2.5Sn	Yield Strength Tensile Strength Elongation, 2" Sheet Bend, 105°	= 110,000 Psi min = 115,000 Psi min = 15 Pct min. = Under 0.070" - 3T Over 0.070" - 3.5T
Ti-6Al-4V	Yield Strength Tensile Strength Elongation, 2" Sheet Bend, 105°	= 120,000 Psi min = 130,000 Psi Min = 10 Pct min. = Under 0.070" - 4.5T Over 0.070" - 5T

TMCA* Titanium Metals Corporation of America

APPARATUS

Automatic welding processes provide accurate control of the essential variables: inert gas atmosphere, arc-length and welding speed. In practice, manufacturers have demonstrated that automatic welding processes may be applicable to 90% of the total weld-length of a structure.(2)

A machine was constructed so that weldments could be prepared using a gas cooled welding head containing a 0.040" 2% thoriated tungsten electrode. The welding torch is mounted in a stationery position, and arc-length and angle of approach are set manually. The material to be welded is clamped in place on a speed controlled table. Besides inert-gas issuing from the welding head auxiliary shielding is provided by means of a trailing shield and a recessed compartment below the weld. A voltmeter and ammeter are incorporated into the welding circuit.

A description of the welding machine is detailed in Appendix I.

WELD AND TEST PROCEDURES FOR COMMERCIAL TITANIUM

The titanium strip was prepared for welding by shearing to 3" lengths. The matching edges were ground square. The surfaces were buffed with a stainless steel wire buffer and degreased by washing in acetone. The electrode was polished with emery paper and washed in acetone before a welding run.

The prepared plates were clamped in position on the brass chill bars, with the abutting edges centered over the recessed compartment. Several weldments were completed to establish suitable current settings, voltages, welding speeds and arc-lengths. Two grades of argon, commercial purity (99.995%) and high purity (99.999$^+$%) were used. The under-bead in all cases had a silvery gray appearance. The upper chill bar gap, when less than 3/8" rapidly increased the required amperage for full penetration with very little reduction in the necessary argon cover for clean welds. A larger gap increased the argon requirements with little or no decrease in amperage.

Variations of torch nozzle sizes indicated that the minimum size nozzle of 9/16" gave clean, uncontaminated surface welds with commercial pure argon.

Weld color is the only nondestructive means of evaluating shielding conditions. A silvery gray color of the welds indicates nearly perfect shielding.(5) All discolored welds were discarded. The tests performed on the

welded joints consisted of tensile, bend, hardness and metallographic examination.

Tensile Tests

Tensile tests were conducted to determine the relative strength of the weld to the parent metal. Tension test specimens, figure no. 1, were of the flat-bar type with a reduced section 2½" long. The reduced section width was 3/8" and the full plate thickness was used. Details of the method of selection of tensile specimens from the weldments are shown in figure no. 3. Weld irregularities were ground flush with the base metal. Tensile yield strength was determined at 0.2% offset, and elongation was measured over a 2-in. gage length. The weld in each case was in the centre of the reduced section. Results showed a joint efficiency of 100%. Consequently the measured tensile strength and yield strength pertained to the base metal only. Micrometer measurements indicated no reduction in the weld section. Therefore, elongation was not a good measure of weld ductility.

Bend Tests

Bend tests were performed to determine weld ductility. Manufacturer's specifications list angle of bend around a specified radius as a criterion for ductility. Free bend tests were carried out on a Hounsfield Tensometer, figure no. 4. The bend attachment was designed

Figure no. 1 -
Modified Tensile
Test Specimen.

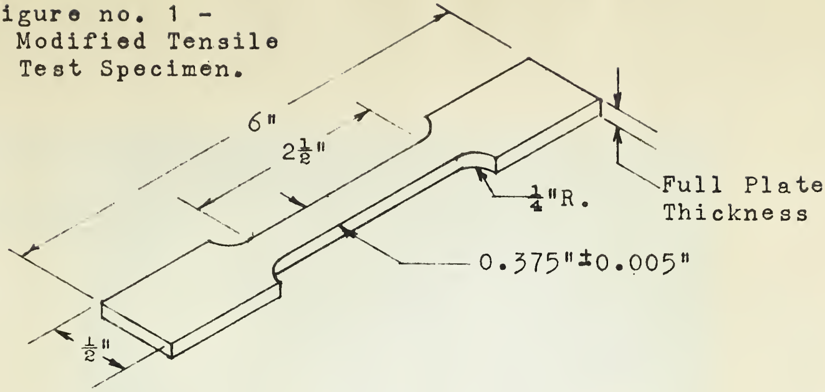
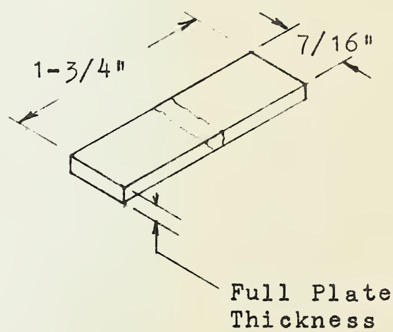


Figure no. 2 -
Modified Bend Test
Specimen



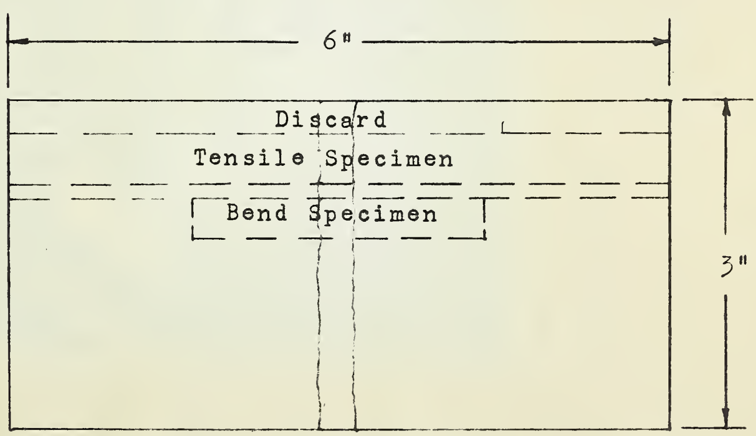


Figure no. 3 -
Method of Selecting Bend and Tensile Specimens

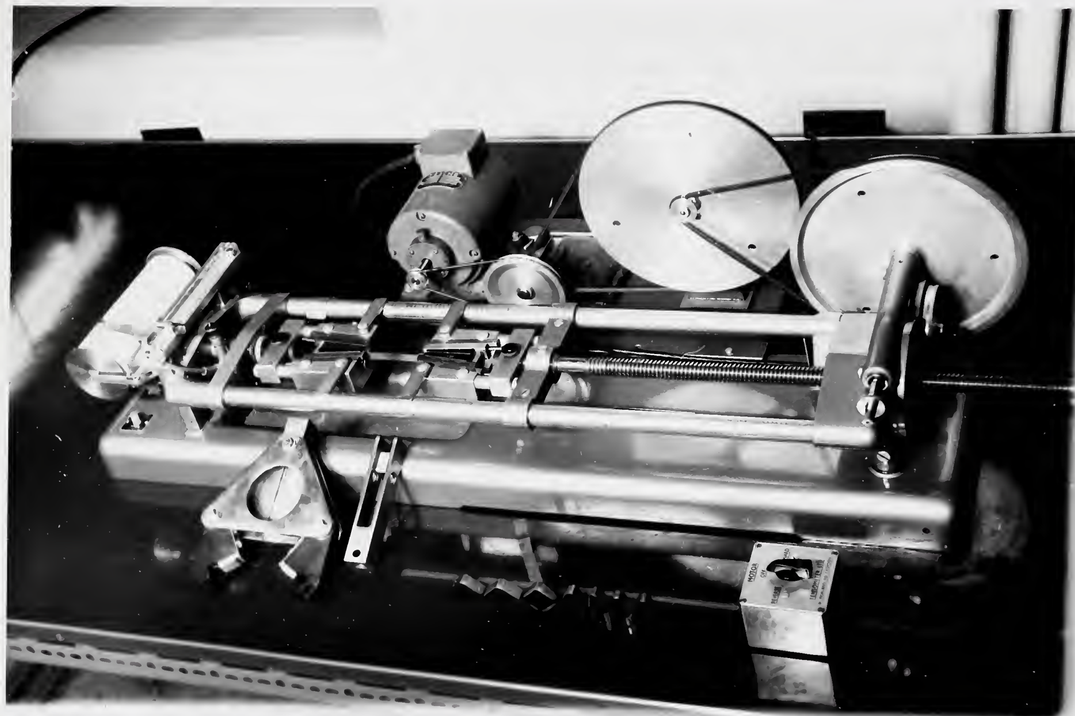


Figure no. 4. - Hounsfield Tensometer - assembled for thin plate tensile tests. Left foreground is modified free bend test attachment.

for 5/16" x 15/32" x 2" test pieces. It was necessary to modify this equipment for thin plate. This was accomplished by brazing 1/4" spacers to the rolling cams and incorporating a 0.05" bend die. These modifications allowed face and root bend properties of thin plate to be evaluated.

Bend specimens suitable for these modifications are shown in figure no. 2.

Weld ductility was established by comparison with unwelded base metal bent over similar radii. The Hounsfield Tensometer enabled the maximum bend load to be recorded. The maximum angle of bend was 120°, due to the design of the equipment. All the welds, and the base metal, tested without failure. The maximum load for the weld bend was slightly higher than for the base material.

To determine the maximum bend before failure several specimens were flattened in a vice. The weld specimens failed at approximately 175°, whereas, the base metal was flattened without failure. Results showed the welds to have good ductility, well above the minimum specifications that are shown in Table 1, but slightly less than the unwelded base material.

Hardness Tests

Diamond pyramid hardness measurements were taken with a Tukon Tester (1000 gr. load) in the base metal, heat-affected zone and the weld area. The results showed increasing hardness to the center of the weld. The maximum

difference was 40 diamond pyramid hardness units. (Table 2)

Metallographic Examination

Metallographic examination revealed the base metal to be an equiaxed, fine-grain structure. The weld-metal and heat-affected zone were coarse-grained acicular structures. A narrow band of the heat-affected zone adjacent to the base metal showed slight coarsening of the grain and traces of an acicular structure.

Summary

The results of these tests indicated that the equipment and procedures were suitable for welding strip titanium. The particular welding procedure developed for the preceeding welds is shown in Appendix II.

TABLE 2 - Hardness Traverse (D.P.H. 1000-gr. load) on Weld of Commercial Titanium

Location of Indentation	Diamond Pyramid Hardness
Base Metal	193
Base Metal	198
Base Metal	203
HAZ*	209
HAZ	217
HAZ	216
HAZ	210
Weld	216
Weld	220
Weld	221
Weld	210
Weld	216
Weld	208
HAZ	217
HAZ	209
HAZ	216
HAZ	223
Base Metal	193
Base Metal	203
Base Metal	191

* Heat-affected Zone

ALPHA ALLOY (Ti-5%Al-2.5%Sn)

Visual inspection of the weld surface revealed inadequate shielding. A trailing shield was attached to the torch to increase the time for which the weld could be protected by inert atmosphere. This produced welds with the desired silvery gray color.

TESTS AND RESULTS

Tensile Tests

The tensile properties of the welded material and base metal are shown in Table 3. All the fractures occurred in the base metal, indicating a joint efficiency of 100%. There was no measurable reduction of area in the weld section.

Bend Tests

The bend radius was 5/32", that is 3T, where the thickness of the material is T. The results of the bend tests are shown in Table 3. These results show that the weld has greater ductility than the base metal. Fracture occurred in each weld specimen in the heat-affected zone adjacent to the base metal. There was no significant difference between root and face bend ductility.

Hardness Tests

Hardness traverses were taken across the weld, heat-affected zone and base metal as shown in Table 4.

TABLE 3 - Tensile and Bend Properties for Ti-5%Al-2.5%Sn

Specimen	Yield Stress .02% Offset psi	Ultimate Tensile Stress psi	% Elongation on 2"	Joint Eff. %	Rad. of Bend	Angle of Bend
Weld #1	113,000	120,000	12	100+	3T	119°
Weld #2	113,000	118,000	14.6	100+	3T	124°
Weld #3	116,000	121,000	12.5	100+	3T	120°
Weld #4	117,000	124,000	15.6	100+	3T	118°
Weld #5	111,000	116,000	16.4	100+	3T	126°
Base Metal #1					3T	109°
Base Metal #2					3T	106°

TABLE 5 - Tensile and Bend Properties for Ti-6%Al-4%V

Specimen	Yield Stress .02% Offset psi	Ultimate Tensile Stress psi	% Elongation on 2"	Joint Eff. %	Rad. of Bend	Angle of Bend
Base Metal:						
As-received	123,000	132,000	12.5		3T	120°
S.R. 850°C in air					3T	84°
S.R. 850°C in air and descaled	125,000	139,000	10.5		3T	112°
S.R. 850°C in argon					3T	119°
Welds:						
As-welded	128,000	145,000	6.3	100	3T	67°
S.R. 750°C in argon					3T	86°
S.R. 800°C in argon					3T	91°
S.R. 850°C in argon	124,000	138,000	10.9	100	3T	113°
S.R. 900°C in argon					3T	100°
S.R. 950°C in argon					3T	98°
S.R. 1000°C in argon					3T	65°
S.R. 850°C in air					3T	5°
S.R. 850°C in air and descaled	125,000	141,000	9.4	100	3T	111°

S.R. - Stress relieve fifteen minutes at temperature and furnace cool.

TABLE 4 - Hardness Traverse (D.P.H. 1000-gr. load) on Weld of Ti-5%Al-2.5Sn

Location of Indentation	Diamond Pyramid Hardness
Base Metal	292
Base Metal	307
Base Metal	293
HAZ*	324
HAZ	303
HAZ	323
HAZ	345
Weld	353
Weld	309
Weld	330
Weld	311
Weld	323
Weld	350
HAZ	340
HAZ	326
HAZ	302
HAZ	320
Base Metal	308
Base Metal	309
Base Metal	287

* Heat-affected Zone

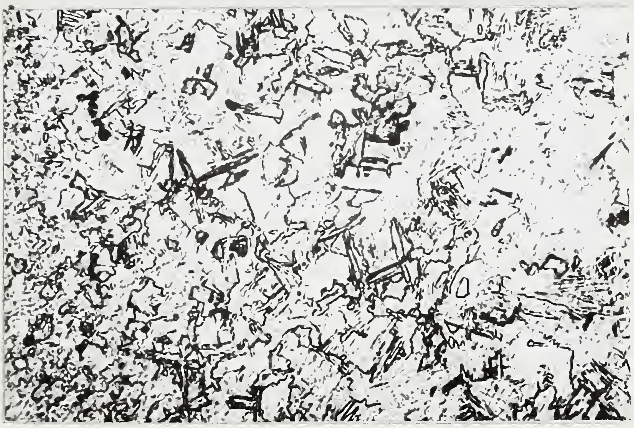
There was a slight increase in hardness in both the weld and heat-affected zone above that of the base metal. One area in the weld showed a hardness slightly lower than the base metal hardness.

Metallographic Examination

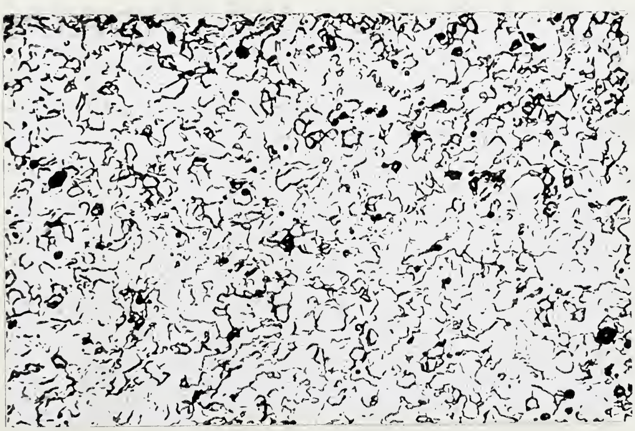
Microstructures of the weld, heat-affected zone and base metal are shown in figure no. 5. The base metal was an equiaxed fine-grained structure.

The weld and adjacent heat-affected zone grain structure consisted of coarse, acicular needles within large former beta grains. The heat-affected zone adjacent to the base metal showed slight grain enlargement and very short acicular needles.

(a) Weld Area



(b) Heat-affected Zone



(c) Base Metal

Figure no. 5. - Typical microstructure (x100) of Ti-5%Al-2.5%Sn weldment prepared in 0.050" strip.

Etchant: Etched in 2% HF in water with $4\%HNO_3$ rinse.

ALPHA-BETA ALLOY (Ti6%Al-4%V)

The additional protective atmosphere supplied by the trailing shield was necessary to produce uncontaminated welds in this alloy, as in the alpha alloy.

Postweld Heat Treatment Procedure

The welds were furnace heated in an argon atmosphere, held at temperature for fifteen minutes, then furnace cooled at a rate of approximately 5° per minute. To prevent oxidation the specimens were wrapped with zirconium wire and placed in molybdenum containers. The specimens and molybdenum container were washed in acetone, and dried before being placed in the furnace. The air was evacuated from the furnace at 400°C to a pressure of approximately 10^{-4} mm. mercury and flushed three times with high purity argon. A slight positive pressure of argon was maintained during the heat treatment cycle.

Postweld heat treatments consisted of stress relieving by heating to temperatures above and below the transformation temperature. The approximate transformation temperature of 860°C for this alloy, was calculated from the binary equilibrium diagrams of titanium-aluminum and titanium-vanadium. The sub-critical heat treatment temperatures were 750, 800 and 850°C: the super-critical heat treatment temperatures were 900, 950 and 1000°C.

The effects of stress relieving at 850°C in air, followed by descaling, were also studied.

TESTS AND RESULTS

Tensile Tests

Table 5 lists the tensile properties of the as-welded and heat-treated specimens. The joint efficiencies were, in all cases, 100%.

Bend Tests

The bend test results are shown in Table 5. The bend ductility of the as-welded specimens was very low. The best angle of bend was obtained on welds that had been stress relieved at 850°C. Samples heat-treated above 850°C showed a lower ductility than those stress-relieved at 850°C. There was no significant difference between face and root bends.

All fractures were intergranular and occurred in the coarsened heat-affected zone at, or near, the weld boundaries, figure no. 6.

Hardness Tests

Table 6 lists the hardness values obtained in a traverse of an as-welded specimen, and the hardness values for each heat-treated specimen. The as-welded specimen showed a significant hardness increase in the heat-affected zone and weld metal above that of the base metal. The hardness of the weld and heat-affected zone was uniform.

The general effect of postweld heat treatment was a decrease in the hardness. The average base metal

Figure no. 6. - Microstructure of intergranular fracture in coarsened heat-affected zone of weldment of Ti-6%Al-4%V (x100).

Etchant: Etched in 2% HF in water with 4% HNO_3 rinse.

TABLE 6 - Hardness Traverse (D.P.H. 1000-gr. load) on Weld of Ti-6%Al-4%V

Location of Indentation	Diamond Pyramid Hardness Numbers for Welds: As-welded	Postweld Heat Treatment Temperature 750°C	800°C	850°C	900°C	950°C	1000°C
Base Metal	320	302	318	302	292	312	303
Base Metal	322	305	304	310	302	289	300
Base Metal	318	314	313	312	293	298	287
HAZ*	350	322	320	318	300	293	311
HAZ	363	318	325	313	309	298	303
HAZ	361	309	333	329	303	292	301
HAZ	366	345	350	340	302	288	303
Weld	347	356	340	348	330	342	331
Weld	358	340	322	330	298	331	314
Weld	361	324	333	326	302	312	301
Weld	350	339	333	326	290	324	307
Weld	363	344	320	309	302	311	302
Weld	358	334	340	324	303	308	330
HAZ	356	352	339	343	320	329	319
HAZ	358	329	318	312	308	291	312
HAZ	366	321	304	323	308	303	309
HAZ	363	309	313	326	303	298	306
Base Metal	334	322	320	305	314	307	288
Base Metal	319	306	308	303	298	284	301
Base Metal	323	305	323	313	298	302	297

* Heat-affected Zone

hardness decreased as the heat treatment temperature increased. The heat-affected zone showed a marked decrease after heat treatment at 750°C, and at higher temperatures the decrease in hardness corresponded to the decrease in hardness of the base metal. In the weld metal the most marked hardness decrease occurred after heat treatment at 800°C. At higher temperatures the hardness was reduced more gradually, and was similar in extent to the decrease in hardness of the base metal.

There was a hard zone at the junction of the heat-affected zone and the weld metal in each specimen heat-treated above 750°C.

Metallographic Examination

The fusion zone of the welds in the as-welded condition consisted of a fine acicular structure of alpha prime needles within large former beta grains. This structure is shown in figure no. 7. The narrow band of the heat-affected zone adjacent to the base metal showed some coalescence and coarsening of the grains with a very small amount of acicular structure appearing. The parent metal was a fine-grained slightly elongated alpha structure, figure no. 8. The slightly cold-worked structure indicated the direction of rolling.

The metallographic examination of the heat-treated specimens revealed various changes in structure. After heat treatment at 750°C the weld showed slight coarsening of the acicular alpha prime needles. There was no

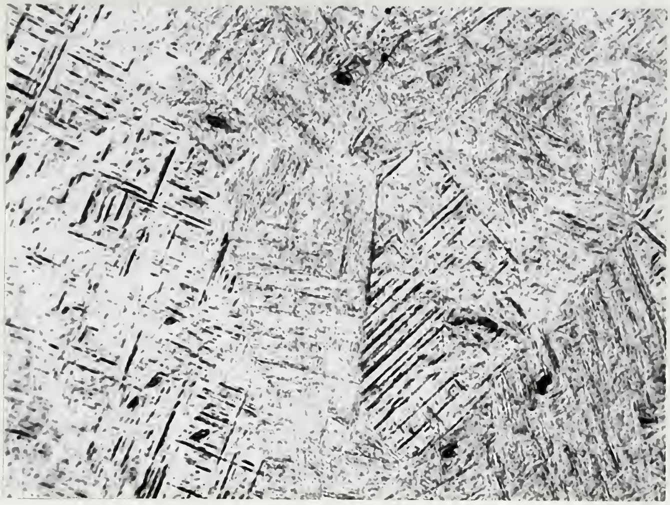


Figure no. 7. - Microstructure of weld metal, as-welded, of Ti-6%Al-4%V (x100), a fine acicular needle-like structure.

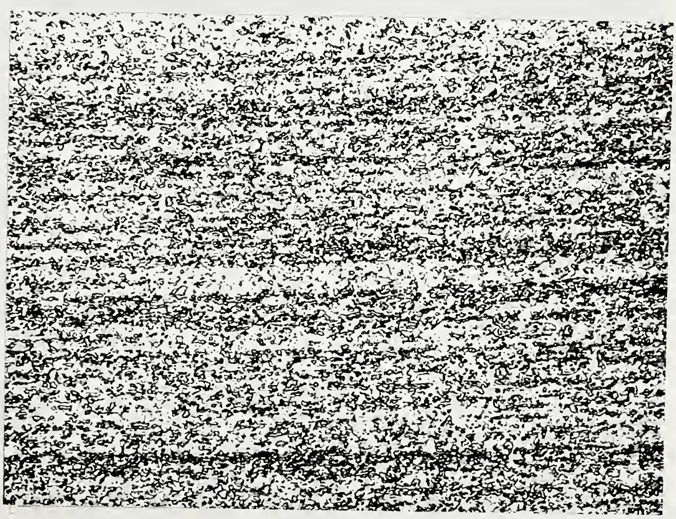


Figure no. 8. - A microstructure of the fine-grained base metal of Ti-6%Al-4%V, as-received, (x100).

Etchant: Etched in 2% HF in water with 4% HNO_3 rinse.

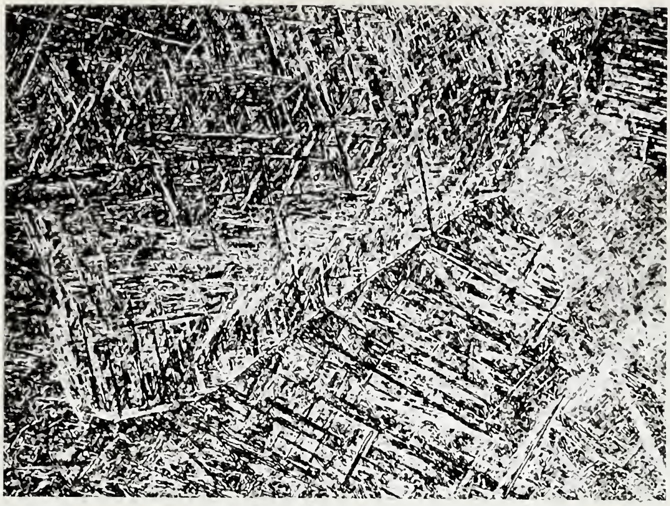


Figure no. 9. - A microstructure of a weld structure after a stress relief heat treatment at 800°C, (x100) of Ti-6%Al-4%V.

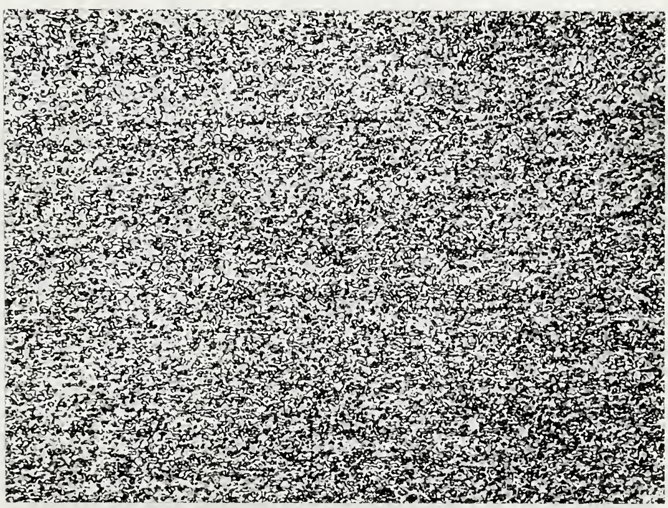


Figure no. 10 - A microstructure of base metal of Ti-6%Al-4%V after a stress relief heat treatment at 800°C (x100).

Etchant: Etched in 2% HF in water with 4% HNO_3 rinse.

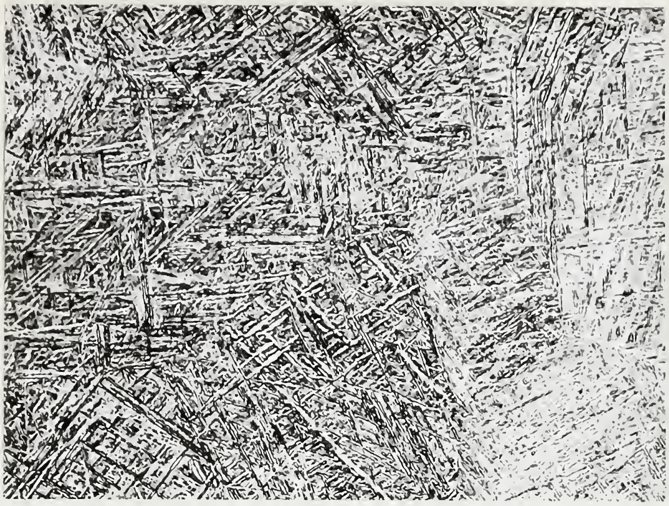


Figure no. 11. - A microstructure of a weld structure of Ti-6%Al-4%V after a stress relief heat treatment at 850°C, (x100).

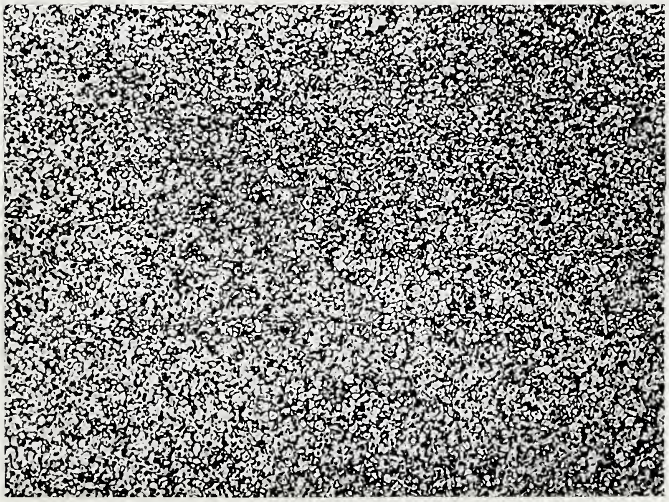


Figure no. 12. - A microstructure of the base metal of Ti-6%Al-4%V after a stress relief heat treatment at 900°C, (x100).

Etchant: Etched in 2%HF in water with 4% HNO_3 rinse.

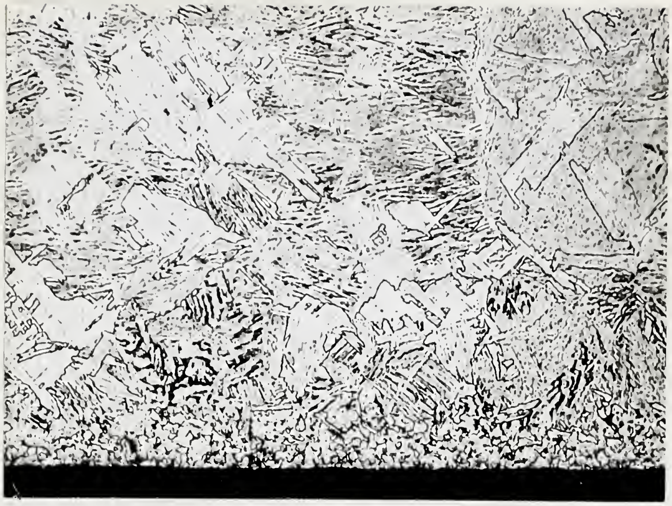


Figure no. 13 - A microstructure of the base metal of Ti-6%Al-4%V after a stress relief heat treatment at 950°C (x100). There is a fine-grained equiaxed structure present in the surface of the base metal.

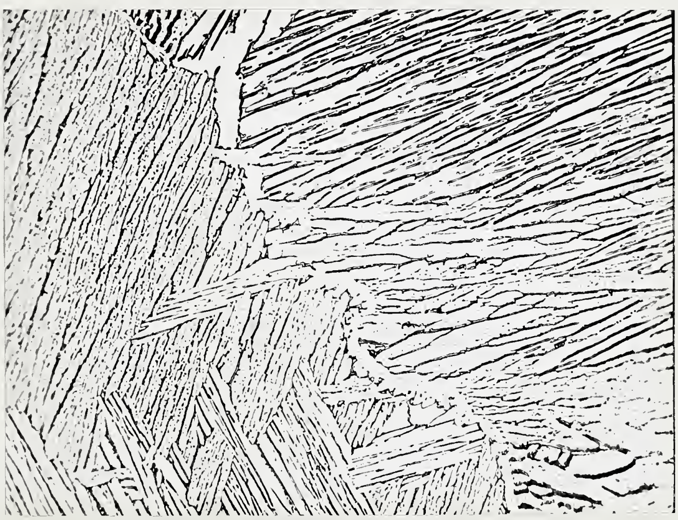


Figure no. 14. - A microstructure of the weld metal of Ti-6%Al-4%V after a stress relief heat treatment at 1000°C, (x500).

Etchant: Etched in 2% HF in water with 4% HNO_3 rinse.

change in the parent metal. The direction of rolling was still apparent. In the specimen heat-treated at 800°C further coarsening of the needle structure had occurred in the weld, figure no. 9. At this temperature the parent metal was beginning to recrystallize, figure no. 10. After heat treatment at 850°C the weld area was beginning to acquire a basket-weave structure, figure no. 11. Further recrystallization had taken place in the parent metal.

After the heat treatment at 900°C the weld had developed a very coarse basket-weave structure. The parent metal at this temperature had a fine, completely recrystallized structure, figure no. 12. After heat treatment at 950°C the weld area showed additional coarsening of the basket-weave structure. At this temperature the parent metal was beginning to show a different structure from the edge to the centre, figure no. 13: a basket-weave structure was observed in the central section; the edge was a fine-grained equiaxed structure. No evidence of this structure appeared in the weld area.

With heat treatment at 1000°C the coarse basket-weave structure in the weld and parent metal were the same. The coarse basket-weave structure comprises broad acicular needles with beta boundaries, figure no. 14. The fine-grained equiaxed structure remained at the edge of the parent metal.

X-Ray Diffraction Analysis

X-ray diffraction analysis was employed to determine the structures present in the weld, heat-affected zone and parent metal. Appendix III outlines the technique used to obtain x-ray diffraction films. It should be noted that the samples used for diffraction studies were cut from the body of the metal and did not include any original surfaces. A photograph was taken of the base metal and of the weld in the as-welded specimen and in each stress-relieved specimen. A comparison of the films disclosed a similar structure in weld and base metal and identical lines on each film.

The diffraction patterns indicated that the structure was almost entirely hexagonal in all cases. Two unidentified lines were observed. These lines did not index according to the beta phase; nor did they correspond to diffraction lines obtained from a purposely contaminated specimen.

Samples Heat-treated In Air

The optimum temperature of 850°C was chosen, and samples were held for fifteen minutes in the furnace, now open to the atmosphere.

Bend tests failed at 5° at the weld centre (see Table 5). Further samples were cleaned by emery cloth and a pickling solution (3 parts HNO_3, 9 parts HCl, 2 parts HF, 5 parts H_2O). Their bend test value was then the same as the base metal value.

DISCUSSION OF RESULTS

The tensile specimens generally broke in the base metal and were of no value in establishing a standard for the weld.

The bend test results showed that the alpha alloy welds have an equivalent ductility to the base metal. In the alpha alloy there was no appreciable increase in hardness in the weld area above that of the parent metal. These results indicate that no embrittlement occurred due to atmospheric contamination or to transformation hardening.

Welds of the alpha-beta alloy that were not heat treated have very little ductility. However, weld ductility equivalent to that of the parent metal may be obtained by a postweld heat treatment at 850°C, either in a controlled atmosphere or in air. When stress-relieved in air the welds require descaling. The bend tests clearly showed themselves to be a useful means of evaluating weld ductility.

Metallographic examination of the alpha-beta alloy revealed that recrystallization occurred at approximately 850°C. This evidence, plus the calculated transition temperature, shows the transformation temperature to be at, or close to, 850°C. The hardness results obtained on the alpha-beta alloy correlate with the bend tests of the welds in the following conditions: as-welded,

heat-treated at 750, 800 and 850°C. As the heat treatment temperatures increased over this range the hardness decreased and the ductility increased, which was to be expected.

The acicular microstructure of the weld area in the as-welded specimens is martensitic. These specimens had low ductility and high hardness values. The acicular structure was coarsened by heat treatment.

Frost[12] has stated that on quenching a "lean" alpha-beta alloy of the Ti-6Al-4V type from a temperature in the beta range no beta is retained. The beta transforms to the hexagonal (alpha prime or titanium martensite) phase. This is a super-saturated alpha phase formed by a martensite-type shear reaction. Unsaturated alpha needles may also form if the cooling rate is slightly lower. The alpha prime structure is not an equilibrium structure and aging will produce mechanical property changes. Simplified, the reaction is believed to be as follows:

$$B_o \longrightarrow a'$$

$$a' \longrightarrow a + B$$

B_o is the original beta phase. Alpha prime is the transition phase, which is super-saturated with beta stabilizing elements, while alpha and beta are the final products.

In conformance with the above theory, and because the chill bar type of quench is not a drastic

quench, the reactions during welding are believed to be:

$$B_o \longrightarrow a' + a$$

$$a' \longrightarrow a + B$$

The absence of beta diffraction lines in the x-ray diffraction analysis indicated the amount of beta to be very small (less than 10%). Essentially then, it appears that after welding the structure consists of close-packed hexagonal phases of both equilibrium and super-saturated composition (a and a'). Probably a trace of beta is retained. Heat treatment at temperatures below 850°C leads to an equilibrium condition comprising principally alpha (of equilibrium composition) with a little beta phase also present. The fact that no beta was seen in the microstructures implies that such beta as was present occurred as a sub-microscopic precipitate.

The decreased hardness and increased ductility after heat treatment below 850°C are due to the breakdown of the martensitic structure and the increase in amount of the more ductile alpha phase.

The welds subjected to heat treatment temperatures above 850°C showed decreasing ductility and decreasing hardness as the heat treatment temperatures increased. As these heat treatments were above the transition temperature grain growth occurred in the beta range. Other investigators[11, 13] have stated that large grain growth is a cause of embrittlement and reduced ductility.

This is possibly the major cause of reduced ductility of the specimens heat-treated at the higher temperatures (900°C and above).

The continued decrease in hardness as heat treatment temperatures increased is a result of the maximum amount of beta being transformed to alpha during cooling from temperature, and a minimum amount of beta being retained. The slow cool through the transformation range permits the beta to alpha transformation to proceed by a nucleation and growth process[9]. No stress relief heat treatment in the beta range appears to increase ductility.

Optimum ductility was obtained at 850°C. At this temperature the weld is completely stress relieved without overcoarsening of the structure.

The fine-grained structure on the surface of the parent metal of the specimen heat-treated at 950°C is believed to be due to additional contaminating elements originally present in the strip. Oxygen and nitrogen are alpha stabilizers, and raise the temperature at which the alpha phase transforms to beta[12]. As a result of the increased oxygen and nitrogen concentration, the beta transus temperature is higher for this portion of the specimen than for the weld or the interior of the specimen. Consequently above their transformation temperature the contaminated regions would be expected to have a smaller

grain size than the clean regions. The appearance of this structure in the parent metal, and not in the weld, indicates there was a retention of these elements during the rolling operation. During welding oxygen and nitrogen are redistributed through the weld. The fact that the fine-grained structure occurred at the surface of the parent metal and not at the surface of the weld metal indicates that the contamination was not due to postweld heat treatment.

The microstructure of the sample stress-relieved at 1000°C contains broad needles of alpha outlined by what is believed to be beta boundaries. The slow furnace cool from the beta field allows the beta to transform as it passes through the alpha plus beta field by a nucleation and growth process. As the alpha grows beta stabilizing elements are excluded by diffusion. The transformation temperature of the remaining beta is lowered as the concentration of the beta stabilizing elements increases. When the critical concentration is reached beta will be retained at room temperature.

All the fractures occurred in the coarsened heat-affected zone at, or near, the weld boundary. This is the result of one of the basic metallurgical difficulties that occur during welding of titanium alloys: the overheating of the base metal adjacent to the fusion zone. This causes embrittlement due to grain growth.(13) Another reason for fractures in the coarsened zone may be the redistribution

of the contaminant elements in the original strip. The as-received base metal is a fine-grained structure with the contaminants widely dispersed throughout the structure,[6] but as indicated earlier, with a higher concentration at the surface. Oxygen, nitrogen and carbon are appreciably more soluble in the alpha phase than in the beta phase and more soluble in the beta phase than in the liquid metal. It is possible, therefore, that the co-existence during welding of the alpha, beta and liquid phases, in which the interstitial impurities have such widely different solubilities, may bring about a redistribution of impurities in the weld metal and heat-affected zone which will on cooling give rise to regions of localized high impurity content.[11] Further, even under near-perfect shielding, extremely small amounts of oxygen and nitrogen may be added to the weld.

When the weld metal is molten the contaminants are most likely to be at the boundary of the liquid and slight concentration occurs at the weld boundary. This is also borne out by the fact that a hard zone was noted in each heat-treated specimen above 750°C. The hardness of this region decreased as the heat treatment temperature increased. This decrease is believed to be due to redistribution caused by diffusion.

Sectioning and metallographic examination revealed no evidence of porosity. It is believed that the plate and joint preparation (a combination of draw filing of abutting edges plus rotary wire wheel brushing the adjacent

surfaces, followed by cleaning with acetone immediately before welding, as suggested by previous investigators[3,4,5,6] is the reason for lack of porosity.

SUMMARY AND CONCLUSIONS

The alpha alloy containing 5%Al-2.5%Sn is readily weldable, has good ductility as-welded and a joint efficiency of 100%.

The alpha-beta alloy containing 6%Al-4%V is weldable, but to have a ductility equivalent to the parent metal requires additional heat treatment. A satisfactory heat treatment consists of stress relieving at 850°C for fifteen minutes in a controlled atmosphere. A similar heat-treatment in air, followed by descaling shows comparable results.

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APPENDIX I

THE WELDING MACHINE

The welding machine is a speed controlled table with a stationery welding torch, figure no. 15.

The welding table consists of a steel plate welded to an 8" x 16" angle frame mounted on grooved wheels. Three of the wheels are fastened to the axles, one wheel is loose. Propulsion is provided by a 1/16 HP electric motor connected through a gear reduction and crown gear and pinion to the axle, with two wheels fixed. A Variac in the motor circuit provides speed control. The machine runs on two rails 14" apart mounted on a Dexion frame 18" x 42" x 36" high. Supports are incorporated in the frame to carry the welding and motor cables and inert gas hoses.

A recessed compartment (figure no. 16) is created by setting a brass bar 1/4" x 4½" x 3/8" deep with a machined groove 1/16" x 3" long between two brass chill bars 4½" x 3" x 3/8" set on the table. 3" x 3" x 1/8" copper chill bars are provided for the top. Two angle clamps are attached to the table to hold in position the chill bars and material to be welded. Inert atmosphere is introduced to the under side of the weld through copper tubing brazed to the frame.

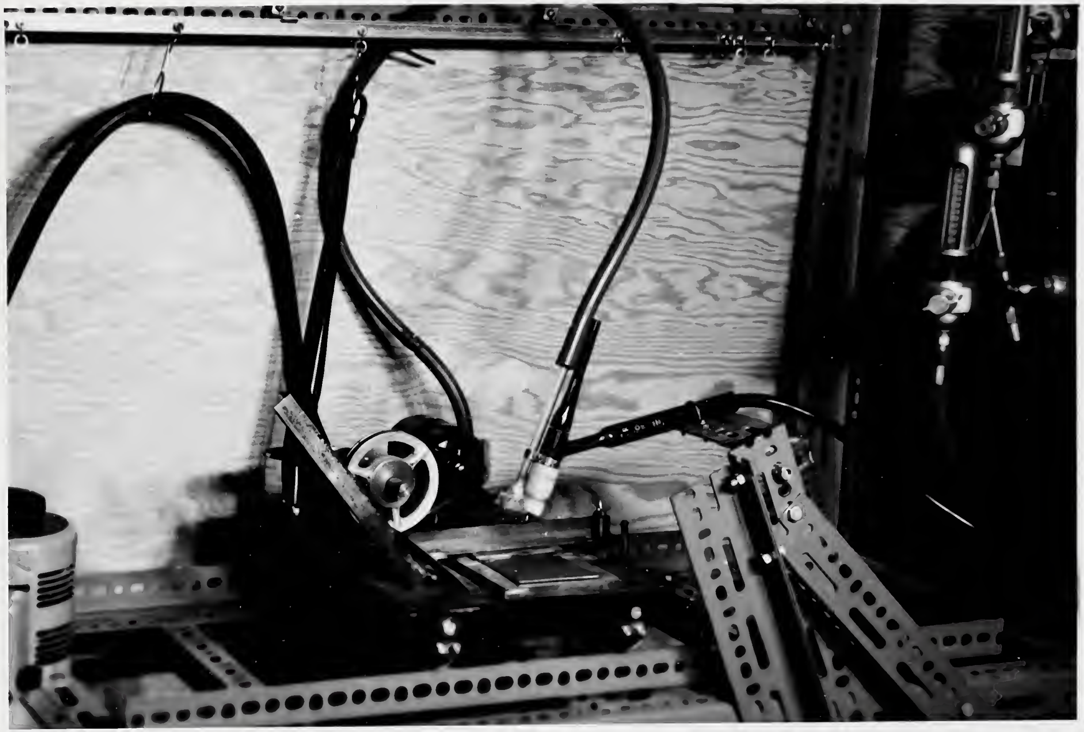

Figure no. 15 - Laboratory Welding Machine for producing flat position welds in thin plate.

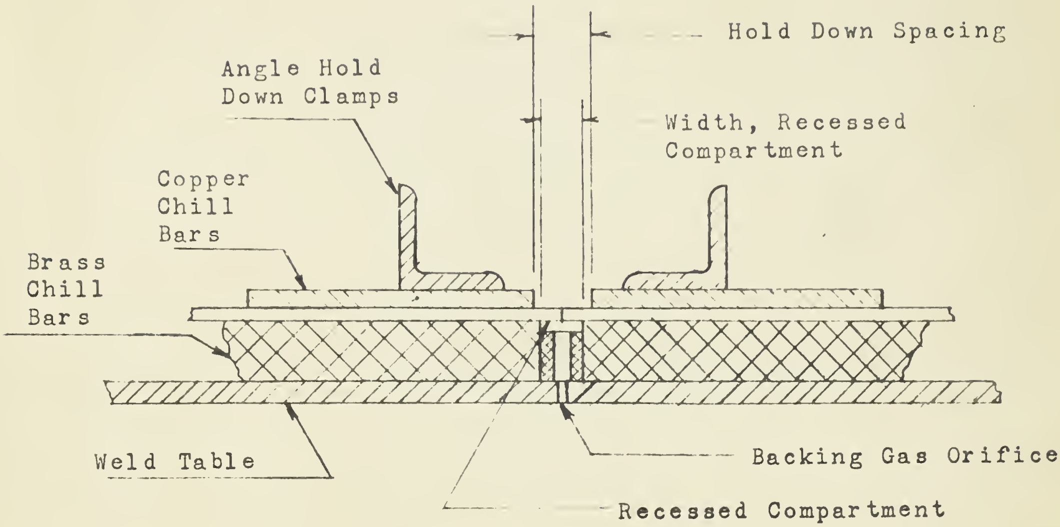

Figure no. 16 - Schematic Outline of Recessed
Welding Compartment.

The torch is designed to conduct gas to the surface of the weld. A trailing shield atmosphere is accomplished with a glass funnel diffuser mounted on the welding torch and connected by a tee to the inert gas source on the work table. The welding torch, a Heliarc HW-17, is fastened to a cantilever beam which is attached to the frame. The lever has a swivel attachment to allow vertical adjustment of the head to control arc length. The torch is attached to the lever to allow lateral adjustment.

APPENDIX II

WELDING PROCEDURES

Power Source	Regent DC Arc Welder (0 to 400 amp.)
Ignition	Regent high frequency unit
Argon	Commercial grade 99.995% pure
Cleaning	Polish with 240 mesh emery cloth; buff with a stainless steel wire brush; wash in carbon tetrachloride or acetone.
Joint Design	Square butt
Material Size	3" x 3"
Polarity	Straight
Open Circuit Voltage	75 volts
Closed Circuit Voltage	28 volts
Electrode	0.040" - 2% thoriated tungsten non-consumable
Arc-length	0.04"

	Titanium	Ti-5Al-2.5Sn	Ti-6Al-4V
Material Thickness	0.030"	0.050"	0.050"
Current (amp.)	30	45	73
Gas Cover:			
Under Side (c.f.h.)*	10	10	10
Torch (c.f.h.)*	25	20	20
Trailing Shield (c.f.h.)*	nil	15	15
Welding Speed (i.p.m.)**	10	8	11
Number of Passes	one	one	one
Preheat	nil	nil	nil
Postheat	nil	nil	stress relieve

* cubic feet per hour

** inches per minute

APPENDIX III

X-RAY PROCEDURE

Machine	Philips X-Ray Diffraction Apparatus, Model PW1009
Camera	Debye Scherrer type Diameter: 57.29 inches
Film	Industrial X-Ray
Target	Copper
Filter	Nickel
Exposure Time	Twelve hours
Tube Voltage	25 KV
Amperage	12 ma.

Specimen Preparation

Samples were selected from the weld area and the base metal. These were turned in a lathe to .025" diameter, etched in an aqueous solution of 50% HF, 25% HNO_3 and 25% H_2O to approximately .005" diameter.